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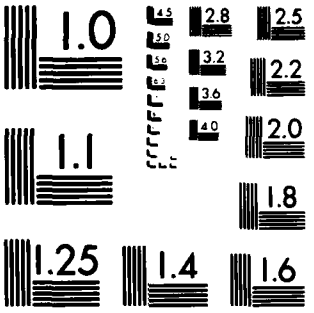

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A field effect transistor with metal gate suspended above the gate insulator has been fabricated. Fluid samples can freely penetrate into the gap formed between the metal and the insulator. If the molecules carry an electrical dipole, they will alter the surface potential on these two materials giving rise to a change in the drain current of the transistor. Our preliminary results confirm this mechanism for dipolar molecules such as methanol and methylene chloride.

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TECHNICAL REPORT NO. 2

FIELD EFFECT TRANSISTORS SENSITIVE TO DIPOLAR MOLECULES

by

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Prepared for publication in the

Applied Physics Letters

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July 5, 1983

A gas sensitive field effect transistor which responds to changes in partial pressure of hydrogen has been invented by Lundstrom, et al., [1]. In that device the signal is derived from a change of the work function of palladium metal which serves as a gate metal in a conventional insulated gate field effect transistor (IGFET) configuration. Because of the unique ability of hydrogen to permeate into solid palladium, this device is highly selective to that species.

In this paper, we wish to report on preliminary results obtained with a general type of field effect transistor in which any fluid sample can freely penetrate into the gate structure. Such a device could be used for detection and measurement of a variety of dipolar molecules, either in liquid or in gaseous phase.

The schematic diagram of the transistor which we have developed for that purpose is shown in Figure 1. It is similar to our previously published device, so called suspended mesh ion sensitive field effect transistor (ISFET) [2]. The transistor channel (1), the substrate Si (2), and the insulator SiO_2/Si_3N_4 (3) have their usual function. The gap (4) between the insulator (3) and the metal mesh (5) can be viewed as an additional insulator with permittivity close to one. When the gaseous molecules with an intrinsic dipole penetrate into the gap they may change inperceptibly its permittivity. However, when they adsorb <u>either</u> on the insulator <u>or</u> on the metal surface in some preferred geometrical orientation, they contribute to the surface potential χ

$$\chi = \frac{1}{\varepsilon_o} \sum_i N_i \mu_i$$

where N_i is the density of adsorbed molecules, μ_i is the vertical component of their dipole moment, and ε_o is the permittivity of free space. This potential is superimposed onto the overall field defined by the gate capacitance and by the applied voltage V_G. The change in the number of adsorbed dipoles will, therefore, give rise to a change in the overall electric field and to the change of the drain current.

The suspended metal mesh was formed on a silicon wafer upon which an array of ISFET chips had already been fabricated. The suspended mesh was formed by fabricating the array of holes in a platinum film over a layer of aluminum. The aluminum was then etched from underneath the platinum mesh through the array of holes, leaving the mesh suspended. A more detailed description follows.

First, a film of aluminum was evaporated on the wafer to a thickness that corresponds to the desired spacing between the metal mesh and the surface of the transistor. In this report, thicknesses of 700 nm and 130 nm were used. Then, a 50 nm film of 10% titanium/90% tungsten (for improved adhesion) was sputtered on the aluminum followed by a 100 nm film of platinum.

A 100 nm film of polyimide (DuPont PI-2550) was then spun-cast on the wafer, followed by a prebake at 135°C for 60 minutes. The array of holes, defined by a positive photoresist mask (Shipley AZ-1370), was then etched in the polyimide film using Shipley AZ-351 developer. The polyimide and photoresist films were then postbaked at 300°C fo 60 minutes.

With the holes defined in the polymer layer, the platinum and titanium/tungsten layers were removed from within the holes by etching in an

argon ion mill (500 eV beam, 0.05 mA/cm^2, 3 x 10^{-4} torr Ar) for 30 minutes. The underlying aluminum protected the surface of the chip during milling.

The aluminum was then etched from the chip and from underneath the platinum by immersion in a solution of 1.25% (v/v) acetic acid, 1.25% nitric acid, and 20% phosphoric acid for 90 minutes at 55°C. During this aluminum etch procedure, the titantium/tungsten was simultaneously etched from the underside of the platinum mesh. Also, the polyimide and photoresist films lifted off the top surface, leaving only platinum in the mesh area. Subsequent rinsing and drying left the mesh suspended, with air filling the space between the platinum and the transistor surface. A scanning electron micrograph of the complete device is shown in Figure 2.

The air-gap acts as an additional insulator which lowers the sensitivity of the transistor; the transconductance of the conventional IGFET is $g_m = (\frac{\partial I_D}{\partial V_G})_{V_D=2V} = 8.1 \times 10^{-4}\,\Omega^{-1}$, whereas for the otherwise identical transistors with 0.7 μm air gap, $g_m = 2.3 \times 10^{-5}\,\Omega^{-1}$.

Evidently there is some sagging of the metal mesh which is distinguishable under high magnification scanning electron microscopy. This sagging is negligible for devices with > 700 nm spacing. These devices, however, have low g_m and therefore a low signal-to-noise ratio. For a narrower spacing (130 nm), the sagging becomes significant to the extent that the final gap is probably 10 nm or less. This has been established by comparing the g_m values for the same transistor in air and in liquid methanol. These devices, nevertheless, show a good sensitivity to gas and an excellent signal-to-noise ratio.

The chemical response of the device has been tested under flow conditions by injecting 5 μl of tested substance into a 5 ml evaporation

chamber from which it was flushed out in exponential manner past the FET. The purpose of these tests was to verify the concept of these devices. No attempt has been made to optimize the conditions of these experiments. The response curves are shown in Figure 3. The lack of response to pentane and to other non-polar molecules confirms the concept of the change of surface potential. The initial, fast response signal which is followed by the strong, slow positive response which was obtained upon addition of methanol or methylene chloride could be due to different kinetics of adsorption and/or orientation of these molecules on the platinum and/or silicon nitride surface and will be the subject of future study. The long time required for the signal to return to its pre-injection value may be due to slow desorption from the FET surfaces or slow desorption from the walls of the evaporation vessel.

Finally, in order to prove that this device could be used for the measurement of adsorption of dipolar molecules from dielectric liquids, we have tested the response to methanol in toluene. The result of this test is shown in Figure 4. It is obvious from these preliminary tests that we have a general type sensor for dipolar molecules. The next step in this study will involve quantification of the response as well as an attempt to modify the surfaces in order to obtain some selectivity.

Acknowledgement

This work was partly supported by a contract from the Office of Naval Research.

References

1. I. Lundstrom, M.S. Shivaraman, and G. Svensson, J. Appl. Phys, 46 (1975) 3876.

2. G. Blackburn and J. Janata, J. Electrochem. Soc., 129 (1982) 2580.

Figure Captions

Figure 1. The schematic diagram of the device (see text for explanation).

Figure 2. Scanning electron micrograph of the gate area.

Figure 3. The response of the transistor operated in constant drain current (I_D = 0.25 mA) mode to addition of 5 µl of (A) methanol; (B) methanol chloride; (C) n-heptane to a flowing stream of nitrogen.

Figure 4. The concentration response curve for the transistor operated in constant drain current mode (I_D = 0.25 mA) to addition of methanol in toluene at 25°C.

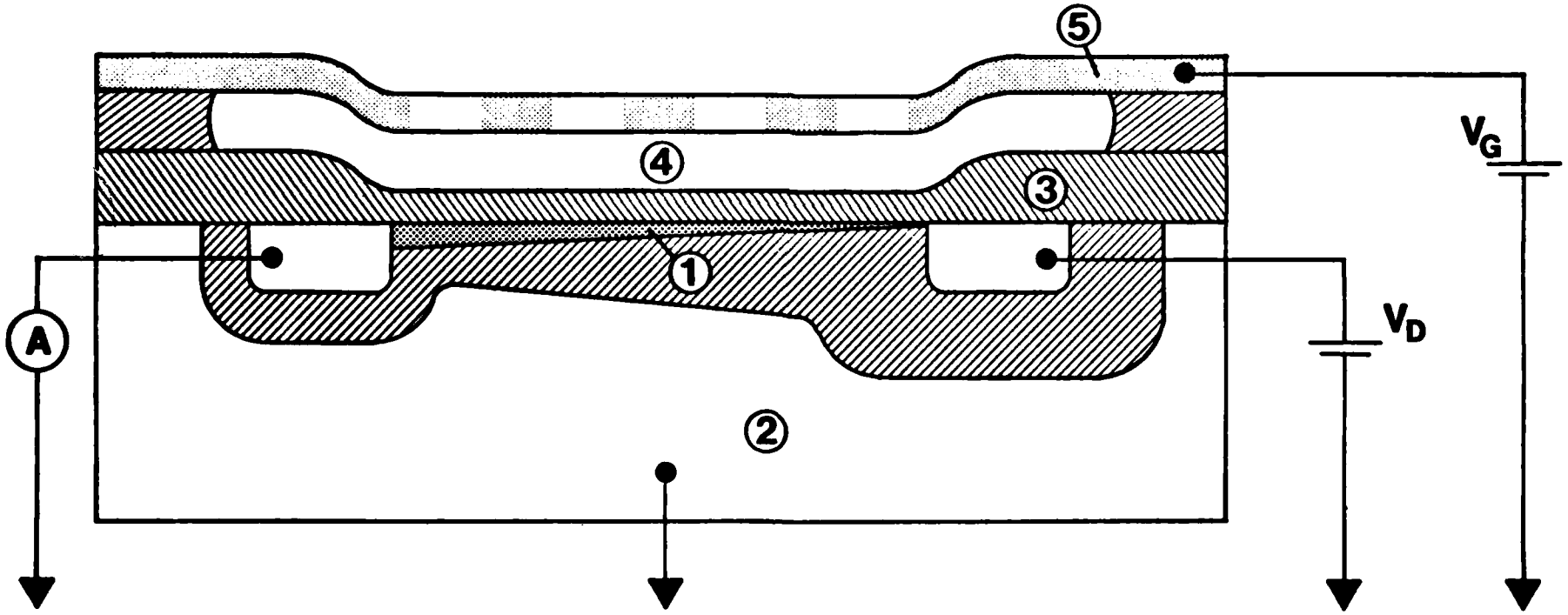


Figure 1

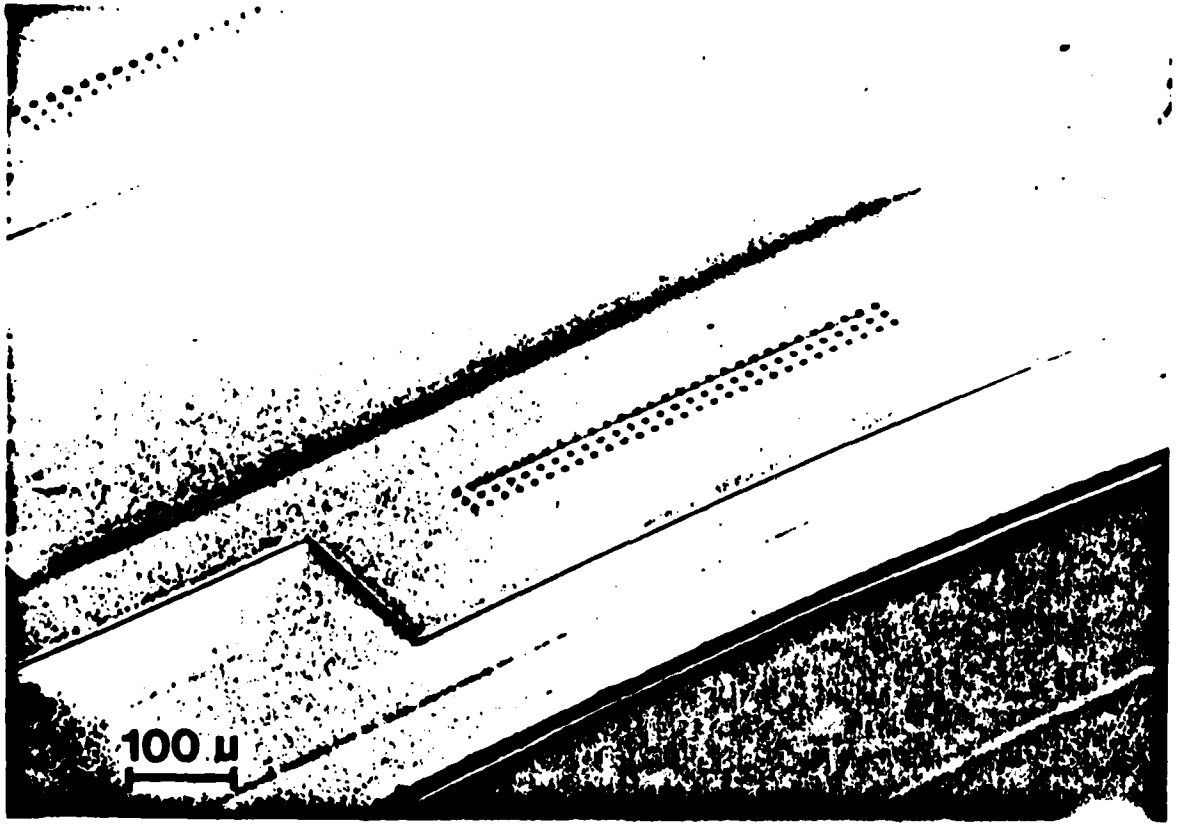


Figure 2

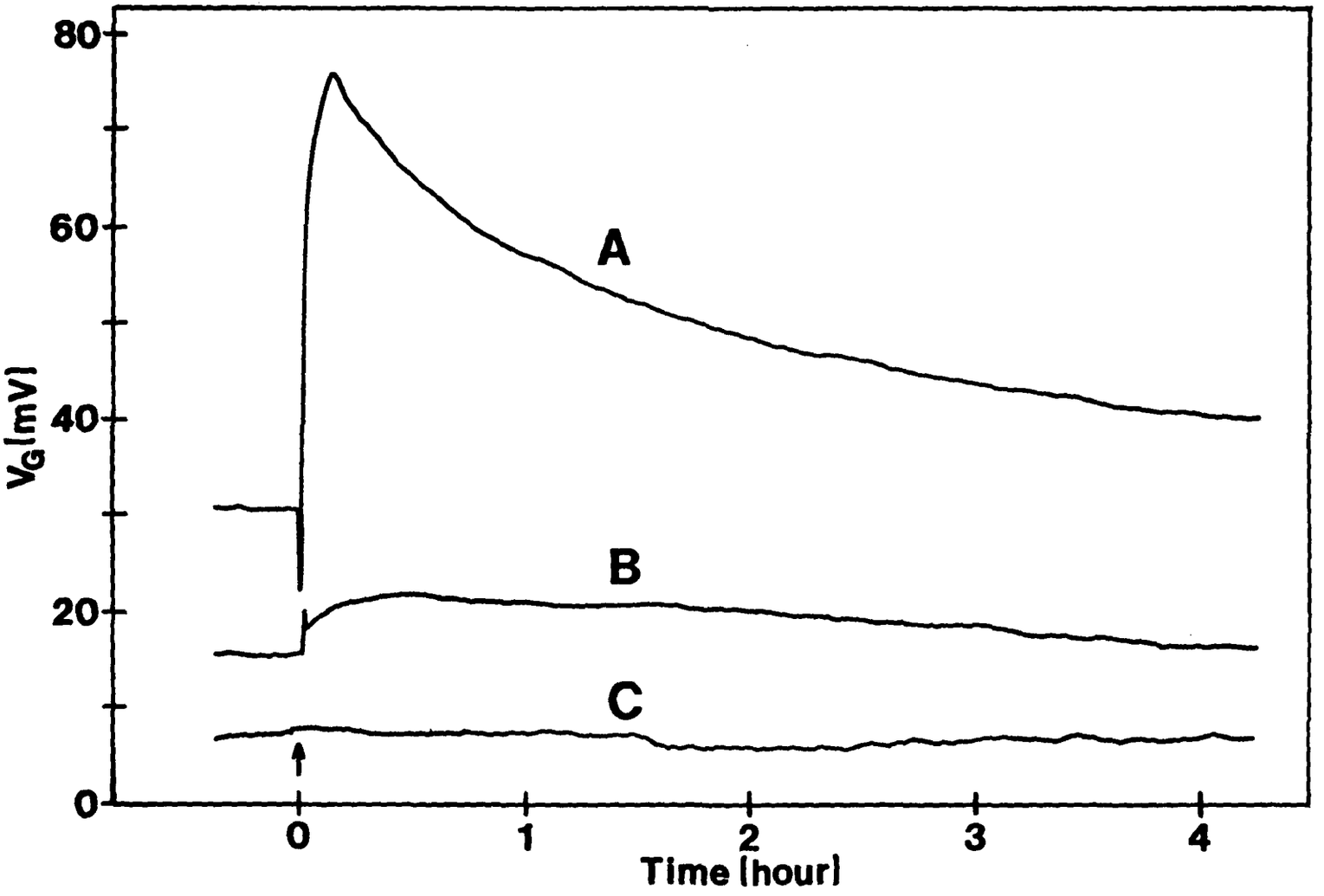


Figure 3

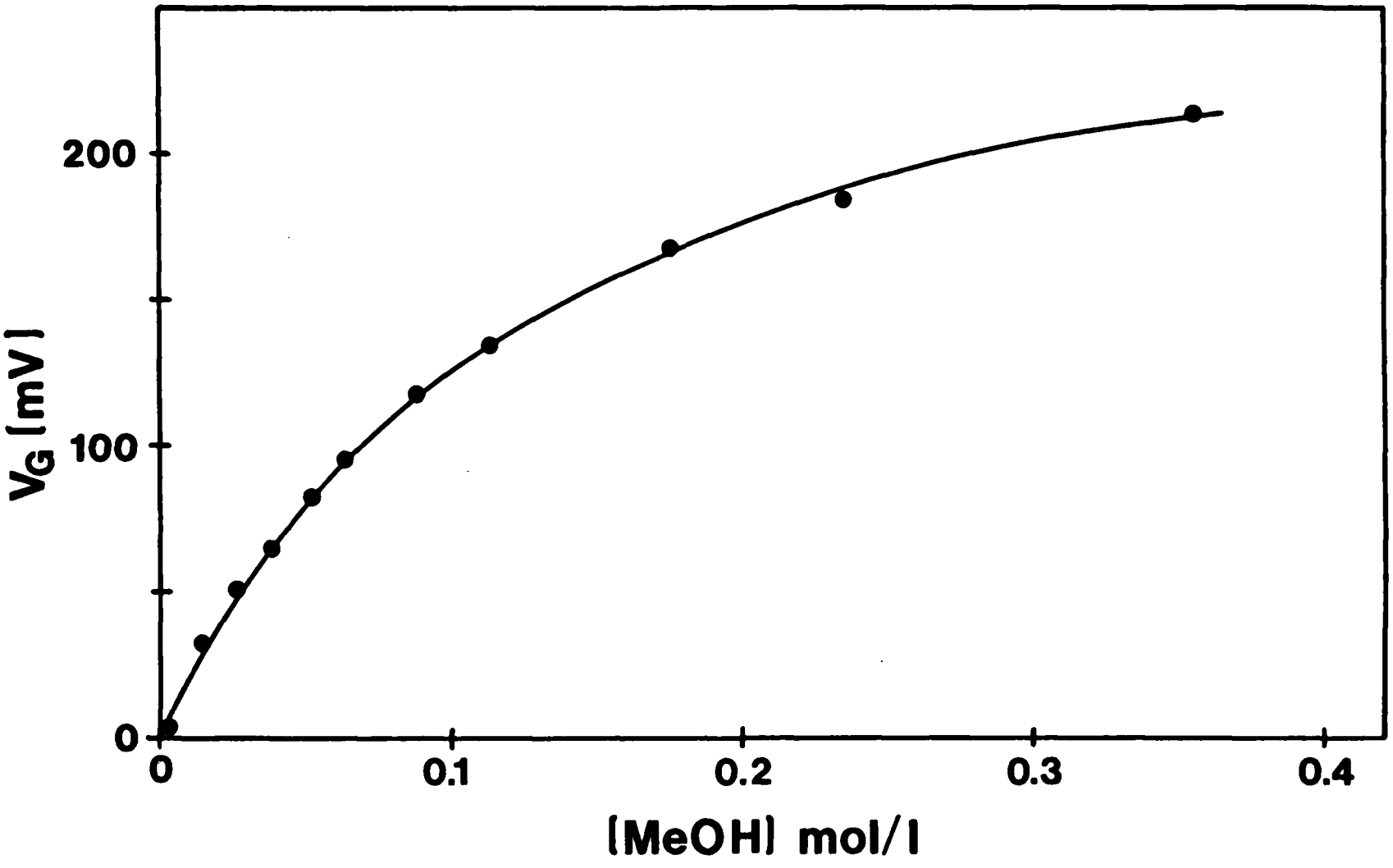
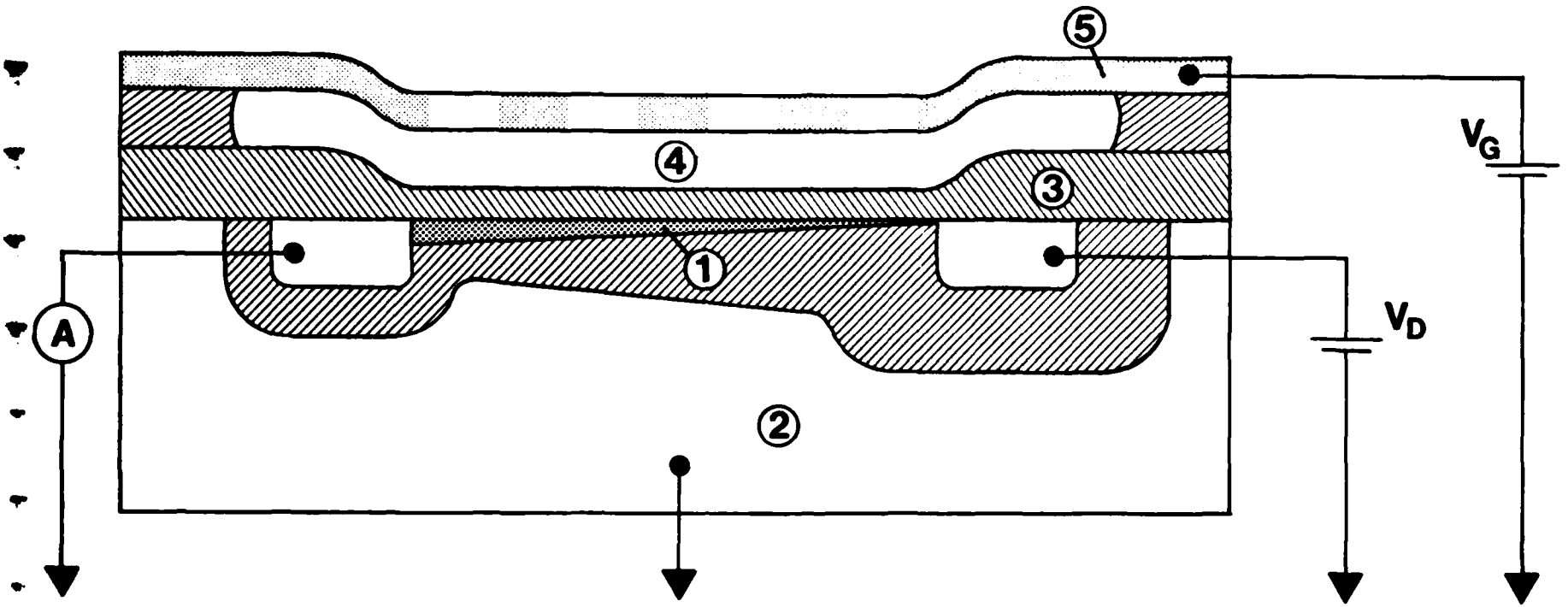


Figure 4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